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SPECTRAL CHARACTERISTICS OF CYLINDRICAL SENSORS OF HYDROPHYSICA--ETC(U)
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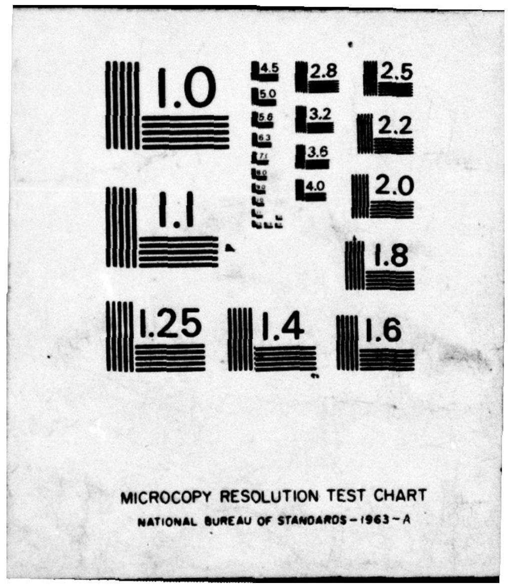
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(Spektral'nyye kharakteristiki tsilindricheskikh datchikov gidrofizicheskikh priborov)

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SPECTRAL CHARACTERISTICS OF CYLINDRICAL SENSORS OF HYDROPHYSICAL INSTRUMENTS

[Dotsenko, S. V., V. N. Kuleshova, and A. N. Nedovesov, Spektral'nyye kharakteristiki tsilindricheskikh datchikov gidrofizicheskikh priborov, Morskoy Gidrofizicheskiy Institut, Trudy, No. 1 (57), 1972, pp. 88-95; Russian]

The article discusses the transformation of the spectrum of the measured field into the spectrum of the output signal by a cylindrical sensor during its uniform linear motion and for two types of orientation. The calculations presented make it possible to construct sensors with specified spectral characteristics. /88*

Various types of measuring instruments are used in hydrophysical studies. The sensors of these instruments have the most diverse configurations. We will study the spectral properties of cylindrical sensors. This group, which is one of the most numerous, includes bathometers, transparency meter sensors, sound velocity sensors, etc.

In many cases, the purpose of measuring physical fields in the ocean is to determine their spectral density (spectrum). We will see how the spectrum of the measured field is transformed into the spectrum of the output signal during a uniform linear motion of a cylindrical sensor, assuming that the field is random, homogeneous, isotropic, and that Taylor's hypothesis of "frozen turbulence" is fulfilled.

If the instrument is moving in a three-dimensional field, the signal at the output of its sensor Y(t) is a four-dimensional convolution with respect to the space coordinates and time of the field $X(\vec{\rho};\tau)$ and instrument function of the sensor $H(\vec{\rho};\tau)$:[1]

$$Y(t) = \int d\vec{\rho} \int_{-\infty}^{\infty} X\left[\vec{V}_0(t-\tau)\ \vec{\rho};\ t-\tau\right] H(\vec{\rho};\tau)\, d\tau, \tag{1}$$

where $\vec{V}_0$ is the velocity of the sensor. We find the autocorrelation function of the output signal

$$\begin{aligned} B_Y(t,t_1) &= \overline{Y(t)\,Y(t+t_1)} = \\ &= \int d\vec{\rho}_1 \int d\vec{\rho}_2 \iint_{-\infty}^{\infty} \overline{X\left[\vec{V}_0(t-\tau_1)-\vec{\rho}_1;\ t-\tau_1\right] X\left[\vec{V}_0(t+t_1-\tau_2)-\vec{\rho}_2;\ t+t_1-\tau_2\right]} \times \\ &\times H(\vec{\rho}_1;\tau_1) H(\vec{\rho}_2;\tau_2)\, d\tau_1\, d\tau_2 . \end{aligned} \tag{2}$$

The averaged quantity under the integral sign is the autocorrelation function of /89
the field $X(\vec{\rho};\tau)$. On the assumption of homogeneity and "frozenness" of the field, this quantity depends only on the difference of the space shifts between the points of measurement, i.e., it has the form $B_X\left[\vec{V}_0 t_1 + \vec{V}_0(\tau_1-\tau_2)+\vec{\rho}_1-\vec{\rho}_2\right]$.

The independence of the expression obtained and hence of integral (2) as a whole from time shows that the output signal of the sensor is stationary. We obtain

*Numbers in the right margin indicate pagination in the original text.

$$B_Y(t_1) = \int d\vec{\rho}_1 \int d\vec{\rho}_2 \iint_{-\infty}^{\infty} B_X\left[\vec{V}_0(t_1+\tau_1-\tau_2)+\vec{\rho}_1-\vec{\rho}_2\right] H(\vec{\rho}_1;\tau_1) H(\vec{\rho}_2;\tau_2)\, d\tau_1\, d\tau_2 . \quad (3)$$

Expressing the correlation function of the field in terms of its three-dimensional spectrum $G(\vec{\alpha})$ with the aid of the relation

$$B_X(\vec{r}) = \int e^{j\vec{\alpha}\vec{r}} G(\vec{\alpha})\, d\vec{\alpha} ,$$

we obtain from formula (3)

$$B_Y(t_1) = \int M(\vec{\alpha}, \vec{\alpha}\vec{V}_0) G(\vec{\alpha}) e^{j\vec{\alpha}\vec{V}_0 t_1} d\vec{\alpha}, \quad (4)$$

where the energy spectral characteristic of the sensor is

$$M(\vec{\alpha}; \omega) = \left| \tilde{H}(\vec{\alpha}; \omega) \right|^2 , \quad (5)$$

and $\tilde{H}(\vec{\alpha};\omega)$ is a four-dimensional Fourier transform of the instrument function. From formula (4), we can easily determine the spectrum of the output signal of the sensor

$$S(\omega) = \frac{1}{V_0} \iint_{-\infty}^{\infty} M\left(\frac{\omega}{V_0}, \alpha_2, \alpha_3; \omega\right) G\left(\frac{\omega}{V_0}, \alpha_2, \alpha_3\right) d\alpha_2\, d\alpha_3 . \quad (6)$$

Let us assume that the sensor of the instrument is lag-free, and the field is isotropic. The first condition signifies that the energy spectral characteristic of the sensor is a function of the wave vector only, $M(\vec{\alpha};\omega) = M_\alpha(\vec{\alpha})$, and the second condition gives $G(\vec{\alpha}) = G(|\vec{\alpha}|)$. Consideration of these conditions makes it possible to write the spectrum of the signal at the output of the sensor in the form

$$S_g(\omega) = \frac{1}{V_0} \int M_\alpha\left(\frac{\omega}{V_0}, \alpha_2, \alpha_3\right) G\left[\sqrt{\left(\frac{\omega}{V_0}\right)^2 + \alpha_2^2 + \alpha_3^2}\right] d\alpha_2\, d\alpha_3 . \quad (7)$$

This expression gives the relationship between the three-dimensional spectrum of the field and the spectrum of the signal at the output of the sensor when the latter is moving in a linear path at constant velocity in the field being measured. Considering the relationship between the three-dimensional spectrum $G(\alpha)$ of the field and its one-dimensional spectrum $G_1(\alpha)$

$$G(\alpha) = -\frac{1}{2\pi\alpha} \frac{dG_1(\alpha)}{d\alpha} ,$$ /90

we obtain a representation of the spectrum of the output signal of the sensor in terms of the one-dimensional spectrum of the field

$$V_0 S_g(\omega) = M_\alpha\left(\frac{\omega}{V_0}, 0, 0\right) G_1\left(\frac{\omega}{V_0}\right) - \int_0^\infty F\left(\frac{\omega}{V_0}, x\right) G_1\left[\frac{1}{a}\sqrt{\left(\frac{\omega a}{V_0}\right)^2 + x^2}\right] dx \,. \quad (8)$$

The first term on the right-hand side of formula (8) is the spectrum of the signal which would exist at the output of the sensor if the latter measured only the field along the straight line passing through its center in the direction of the velocity vector, since the energy spectral characteristic $M_\alpha(\frac{\omega}{V_0}, 0, 0)$ depends only on the wavenumber $\alpha_1 = \frac{\omega}{V_0}$, reckoned along $\vec{V}_0$, and is independent of α_2 and α_3, reckoned at right angles to $\vec{V}_0$.[2] The second term gives the correction to this spectrum, dependent on the manner in which the sensor performs the averaging in the plane perpendicular to the velocity. This term is absent if the sensor has infinitely small dimensions in the cross section. The function

$$F\left(\frac{\omega}{V_0}, x\right) = -\frac{1}{2\pi}\int_0^{2\pi} \frac{\partial}{\partial x}\left[M_\alpha\left(\frac{\omega}{V_0}, \frac{x}{a}\cos\varphi, \frac{x}{a}\sin\varphi\right)\right] d\varphi \,, \quad (9)$$

which enters into formula (8) and is wholly determined by the configuration, dimensions and orientation of the sensor, will be referred to as the function of transverse averaging, since its difference from zero is related to the averaging of the field over the transverse coordinates. The quantity a entering into formula (9) is some characteristic dimension of the sensor.

The following representation is possible for each particular form of the one-dimensional spectrum $G_1(\alpha)$:

$$V_0 S_g(\omega) = M_{eq}\left(\frac{\omega}{V_0}\right) G_1\left(\frac{\omega}{V_0}\right),$$

where $M_{eq}(\frac{\omega}{V_0})$ is the equivalent spectral characteristic of the sensor for the selected type of spectrum. It is readily obtained from relation (8):

$$M_{eq}\left(\frac{\omega}{V_0}\right) = M_\alpha\left(\frac{\omega}{V_0}, 0, 0\right) - \frac{1}{G_1\left(\frac{\omega}{V_0}\right)}\int_0^\infty F\left(\frac{\omega}{V_0}, x\right) G_1\left[\frac{1}{a}\sqrt{\left(\frac{\omega a}{V_0}\right)^2 + x^2}\right] dx \,. \quad (10)$$

Hence it is evident that averaging the field along the straight line of the measurement limits the transmission band of the sensor. This property of the sensor is included in the function $M_\alpha(\frac{\omega}{V_0}, 0, 0)$. Averaging the field in the plane perpendicular to the direction of motion causes an additional narrowing of the transmission band of the sensor. The degree of this narrowing depends on the type of sensor and is included in the second term. The averaging volume of a cylindrical sensor is a cylinder of length a and diameter d. The instrument function of such a sensor is /91

$$H_\rho(\rho_1,\rho_2,\rho_3)=\begin{cases}\dfrac{4}{\pi a d^2} & \text{for } |\rho_1|\leq\dfrac{a}{2} \text{ and } \rho_2^2+\rho_3^2\leq\dfrac{d^2}{4},\\ 0 & \text{in the remaining cases.}\end{cases} \quad (11)$$

Hence, using the Fourier transformation, we will obtain an expression for the three-dimensional spectral characteristic of a cylindrical sensor

$$\tilde{H}_\alpha(\alpha_1,\alpha_2,\alpha_3)=Sa\left(\frac{\alpha_1 a}{2}\right)\Lambda_1\left(\frac{d\sqrt{\alpha_1^2+\alpha_3^2}}{2}\right), \quad (12)$$

where $\Lambda_n(x)=n!\left(\frac{x}{2}\right)^{-n}J_n(x)$, $J_n(x)$ is a Bessel function, and $Sa(x)=\frac{\sin x}{x}$.

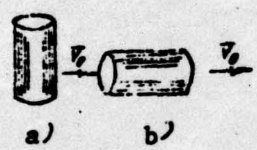

Figure 1. Modes of orientation of cylindrical sensors:
a) transverse orientation; b) longitudinal orientation.

During the measurements, cylindrical sensors can be variously oriented with respect to the direction of their motion. Most typical are measurements with transverse and longitudinal orientation (Fig. 1). Let us first consider the operation of a cylindrical sensor with transverse orientation. The energy spectral characteristic of such sensors is

$$M_{\alpha 1 4}(\alpha_1,\alpha_2,\alpha_3)=$$

$$=S^2a\left(\frac{a\alpha_2}{2}\right)\Lambda_1^2\left(\frac{d}{2}\sqrt{\alpha_1^2+\alpha_3^2}\right), \quad (13)$$

and the transverse averaging function is

$$F_{c\perp}(\nu,q,x)=\frac{2}{\pi}\int_0^{\pi/2}\Lambda_1^2(q\gamma)Sa(\delta)\frac{\sin\delta-\delta\cos\delta}{\delta^2}\sin\varphi\,d\varphi+$$
$$+\frac{xq^2}{4\pi}\int_0^{\pi/2}S^2a(\delta)\Lambda_1(q\gamma)\Lambda_2(q\gamma)\cos^2\varphi\,d\varphi,$$

where the following notation is used: /92

$$\nu=\frac{\omega a}{V_0};\quad x=\alpha a;\quad q=\frac{d}{a};\quad \delta=\frac{x}{2}\sin\varphi;\quad \gamma=\frac{1}{2}\sqrt{\nu^2+x^2\cos^2\varphi}.$$

On the basis of this formula, a numerical calculation of $F_{c\perp}(\nu,q,x)$ was performed for $0 \leqslant q \leqslant 1$ and $0 \leqslant \nu \leqslant 5.0$.

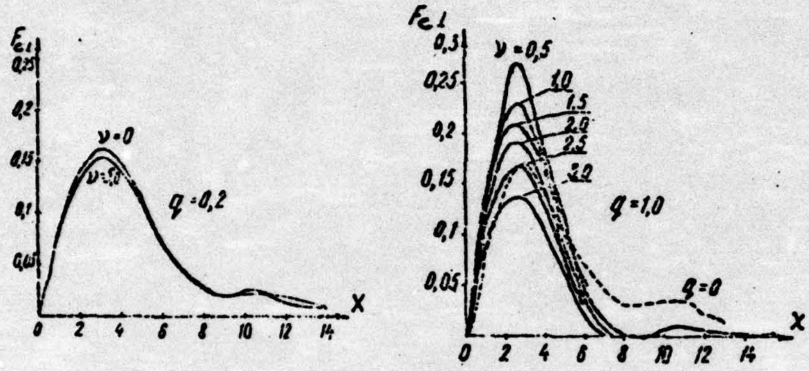

Figure 2. Family of transverse averaging functions of a cylindrical sensor with transverse orientation for different q.

Two families of the graphs of $F_{c\perp}(x)$ obtained for different q and ν are shown in Fig. 2. When $q < 0.5$, the function $F_{c\perp}(x)$ has a significant value only in the region $0 < x < 14$. When $q > 0.5$, this region becomes even narrower. Therefore, in a numerical determination of the integrals including $F_{c\perp}(x)$, the infinite limits /93
may be replaced by these finite ones. Considering the above, we used formula (10) to calculate the equivalent spectral characteristics $M_{c\perp\,eq}(\frac{\omega a}{V_0})$ for sensors with different q and for a field with a different degree of decrease of the spectrum, namely, one obeying the " $\frac{1}{3}$, $\frac{2}{3}$, 1, $\frac{4}{3}$, $\frac{5}{3}$ laws." These plots are given in Fig. 3.

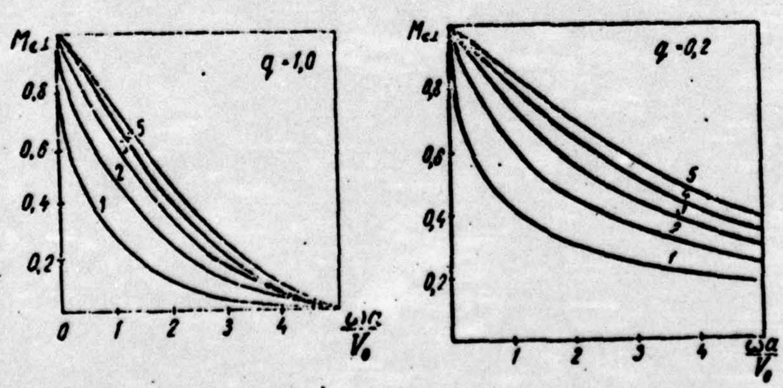

Figure 3. Equivalent spectral characteristics of a cylindrical sensor with transverse orientation for different degrees of decrease of the field spectrum: 1 - " law of 1/3;" 2 - " law of 2/3;" 3 - " law of 1;" 4 - " law of 4/3;" 5 - " law of 5/3."

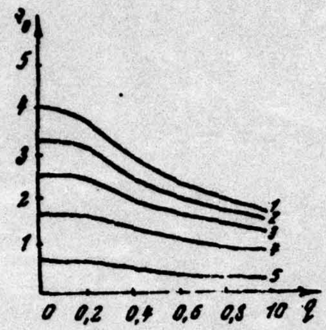

Figure 4. Boundary frequency vs q for different laws of spectral decrease: 1 - "law of 5/3;" 2 - "law of 4/3;" 3 - "law of 1;" 4 - "law of 2/3;" 5 - "law of 1/3."

The family of the dependences of ν_0 corresponding to the condition $M_{c\perp\, eq}(\nu_0) = 0.5$ on q for the above-mentioned laws is shown in Fig. 4. It is apparent from the figures that when $q = \frac{d}{a} \leqslant 0.25$, the spectral characteristics of cylindrical sensors are practically the same as that of a one-dimensional sensor with transverse orientation. The transmission band narrows with increasing ratio $\frac{d}{a}$ and falling degree of decrease of the field spectrum.

Let us consider sensors with longitudinal orientation. The energy spectral characteristic of such a sensor has a form similar to formula (13), but with α_2 replacing α_1,

$$M_{\alpha\parallel c}(\alpha_1,\alpha_2,\alpha_3) = S^2 a\left(\frac{a\alpha_1}{2}\right)\Lambda_1^2\left(\frac{d}{2}\sqrt{\alpha_2^2+\alpha_3^2}\right).$$

Substitution of this relation into formula (8) allowing for formula (9) and some simple transformations give the equivalent spectral characteristic of a cylindrical sensor whose axis is oriented parallel to the direction of motion in the form $M_{c\parallel eq}\left(\frac{\omega}{V_0}\right) = M_{1\parallel}(\nu)\, M_{2\perp\, eq}(\nu_d)$, where $\nu_d = \frac{\omega d}{V_0}$. Introducing $q = \frac{d}{a}$, we finally obtain

$$M_{c\parallel eq}(\nu) = M_{1\parallel}(\nu)\, M_{2\perp\, eq}(q\nu) \tag{14}$$

or

$$M_{c\parallel eq}(\nu_d) = M_{1\parallel}\left(\frac{\nu_d}{q}\right) M_{2\perp\, eq}(\nu_d). \tag{15}$$

When q = 0, equality (14) gives the spectral characteristic of a longitudinal one-dimensional sensor, and when $q \to \infty$, equality (15) gives the characteristic of a transverse disc type sensor. The family of curves $M_{c\parallel eq}(\nu)$ for different q for the " law of $\frac{5}{3}$ " is given in Fig. 5. These plots show that the boundary frequency

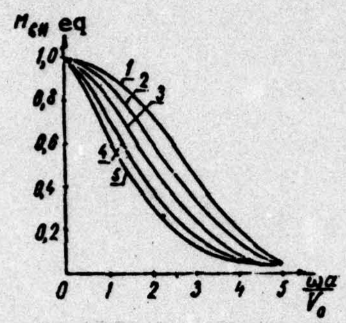

Figure 5. Equivalent spectral characteristics of cylindrical sensor with longitudinal orientation:
1 - q = 0; 2 - q = 0.4; 3 - q = 0.8; 4 - q = 1.2; 5 - q = 1.6.

ν_0, corresponding to the transmission band of the sensor satisfying the condition $M_{c\parallel\,eq}(\nu_0) = 0.5$, can be approximately represented for $q \leqslant 1$ as $\nu_0(q) = 2.8(1-0.39)$. This value differs by not more than 10% from the limiting value ν_0 of a one-dimensional sensor if $q \leqslant 0.25$. Hence, cylindrical sensors oriented parallel to the *direction of motion as well as* sensors with transverse orientation may be considered /94 to be one-dimensional sensors of length a if their dimensions satisfy the inequality $\frac{d}{a} \leqslant 0.25$. On the other hand, when $q > 1$, one can set $\nu_{d0}(q) = 2.6(1 - \frac{0.29}{q})$. Therefore, a cylindrical sensor may be considered a disc if $\frac{d}{a} \geqslant 3.0$. Thus, as the diameter of the sensor decreases and the above condition ($\frac{d}{a} \leqslant 0.25$) is fulfilled, the averaging of the field over the length a of the sensor becomes so much more appreciable than the averaging over the cross section of diameter d, that the latter averaging may be neglected, i.e., the sensor degenerates into a one-dimensional sensor. A cylindrical sensor will have a disc as its "limit" if the condition $\frac{d}{a} \geqslant 3.0$ is achieved as the diameter increases. Moreover, as is evident from the graphs, the transmission band of sensors with transverse orientation is broader than that of sensors with longitudinal orientation.

The above calculations and conclusions make it possible to construct sensors for studying the spectra of physical fields in a region of specified dimensions, or to determine the spectral characteristics of available sensors.

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